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Green building research–current status and future agenda: A review

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ABSTRACT

Green building is one of measures been put forward to mitigate significant impacts of the building stock on the environment, society and economy. However, there is lack of a systematic review of this large number of studies that is critical for the future endeavor. The last decades have witnessed rapid growing number of studies on green building. This paper reports a critical review of the existing body of knowledge of researches related to green building. The common research themes and methodology were identified. These common themes are the definition and scope of green building; quantification of benefits of green buildings compared to conventional buildings; and various approaches to achieve green buildings. It is found that the existing studies played predominately focus on the environmental aspect of green building. Other dimensions of sustainability of green building, especially the social sustainability is largely overlooked. Future research opportunities were identified such as effects of climatic conditions on the effectiveness of green building assessment tools, validation of real performance of green buildings, unique demands of specific population, and future proofing.

Contents

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1. Introduction

Construction industry has significant environmental, social and economic impacts on the society. As one of key outputs of the construction industry, buildings largely reflect these impacts during its lifecycle. The positive impacts of construction activities include: providing buildings and facilities to satisfying human being's requirements, providing employment opportunities directly or indirectly (through other industries related to the construction industry) and contributing toward the national economy. For instance, the construction industry in Australia contributes 7.5% to the Gross domestic product (GDP) and provides more than 1 million jobs. Similarly, buildings and construction activities play a crucial role in urbanization.

The negative impacts of buildings and construction activities are also well recognized. These include the noise, dust, traffic congestion, water pollution and waste disposal during the construction stage. A large quantity of natural and human resources will be consumed. Once completed, buildings continue their impacts on the environment. According to the World Business Council for Sustainable Development, building block accounts for 40% of total energy consumption [1]. Apart from energy consumption, buildings produce Greenhouse Gas emission (GHG) emission which is responsible for global warming. The carbon emission of buildings across the world will reach 42.4 billion tonnes in 2035, adding 43% on the level of 2007 [2]. In addition, the renovation, refurbishment and retrofitting of building will involve the consumption of natural resources and energy; GHG emission; production of noise and other pollutants as well. At the end of life of buildings, the disposal of buildings is also associated with energy consumption and waste production. In 2007, the waste generated from the construction industry in Australia reached 16.6 million tonnes. This accounted for 38% of total waste, of which 43% was sent to landfill [3]. The increasing demand of landfill presents a new challenge to all countries that have issues with limited land. This is compounded by the prediction made by the International Energy Agency that the commercial buildings and institutional buildings will rise two times by 2050 [4].

There are many definitions of green building. For instance, Kibert defined green building as: "… healthy facilities designed and built in a resource-efficient manner, using ecologically based principles" (p.9) [5]. It is worth noting that green building has been used as a term interchangeable with sustainable building and high performance building. Robichaud and Anantatmula pointed out that there are four pillars of green buildings, i.e. minimization of impacts on the environment, enhancing the health conditions of occupants, the return on investment to developers and local community, and the life cycle consideration during the planning and development process [6]. Common elements of these definitions are: life cycle perspective, environmental sustainability, health issues and impacts on the community.

There have been extensive researches on various aspects of green buildings in different contexts. However there is lack of systematic review of existing body of knowledge. Such systematic review plays a critical role to not only identify the common research streams but also highlight the future research trends. This research aims to critically review the green building related studies in a bid to highlight the state of art and future needs in this field. This paper provides a useful reference for both industry practitioners and academics that are interested in green building developments.

2. Common research themes on green building

There have been extensive studies on green buildings, as evidenced in the rapid growing number of papers been published in last decades. These studies have been conducted in both developed countries and developing countries, indicating this is a global issue. A critical review of the existing body of knowledge revealed that there are generally three common focuses of these studies (see Fig. 1). Similarly, green building can be approached either from process (i.e. how to implement the process) or outcome (i.e. how to evaluate the performance) perspective. Management approaches could be significant different depends on the focus. These common themes are discussed in detail in the following sections.

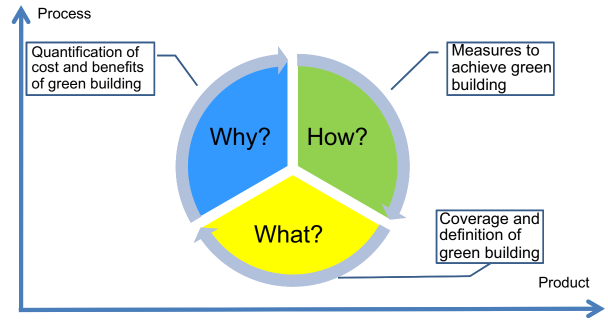


Fig. 1. Mapping of green building related studies.

3. What is green building?

There is a growing level of public awareness of green building. However, there have been extensive debates on what a green building is or what the green building should cover. Indeed, the lack of clear definition of green building creates further challenges for promoting and implementing green buildings.

3.1. Green building assessment tools

A number of assessment tools have been developed to assist the green building developments. The leading green building assessment tools include: Leadership in Energy and Environmental Design (LEED, United States), BRE Environmental Assessment Method (BREEAM, United Kingdom), Green Building Council of Australia Green Star (GBCA, Australia), Green Mark Scheme (Singapore), DGNB (Germany), Comprehensive Assessment System for Built Environment Efficiency (CASBEE, Japan), Pearl Rating System for Estidama (Abu Dhabi Urban Planning Council), Hong Kong Building Environmental Assessment Method (HK BEAM), and Green Building Index (Malaysia). All these green building assessment tools are voluntary rather than mandatory. It was developed by the green building council in each country/region. The assessment is undertaken by accredited professionals that are commissioned by the green building council. The World Green Building Council has been established to coordinate the efforts of various green building councils over the world.

The structures of these green building assessment tools are similar to a large extent, e.g. covering various aspects of sustainability, a number of credits available under each category, different rating tools for various types of projects. For instance, the Green Building Council Australia (GBCA) released eight rating tools (i.e. Education, Office, Industrial, Education, Healthcare, Office Interiors, Retail Centre, Public Building, and Multiunit Residential) with two other pilot tools (Communities, and Interiors). There are nine categories of the GBCA Green Star rating tools, i.e. management, indoor environmental quality, energy, transport, water, material, land use and ecology, emissions, and innovation. Under each category, a certain number of credits (each with some points) are available to apply. The total number of weighted points is 105, including 5 points for the Innovation category. According to the total points achieved, GBCA certified three levels of Green Star

buildings, i.e. 4 Star (achieving 45–59 points, labeled as Best Practice); 5 Star (achieving 60–74, labeled as Australian Excellence); and 6 Star (achieving more than 75 points, labeled as World Leader). Office buildings shared the biggest proportion of GBCA Green Star market, accounting for 60% of total number of green buildings certified by GBCA. In addition, GBCA certified education buildings achieved rapid growth in last 2–3 years.

China has also released similar rating tool called Green Building Label following the Evaluation Standard for Green Building in 2006. The entire process is administrated by the Ministry of Housing and Urban–Rural Development. There are six categories defined in the Green Building Label system, i.e. land efficiency and outdoor environment; energy efficiency and utilization; water efficiency and utilization; material efficiency and utilization; indoor environmental quality; and operation management. Similarly, certain number of points can be awarded to design features of building. Weightings to each category are different for residential or public buildings. The total number of points available is 120, with 10 bonus points for innovation; 10 bonus points for marketability; and 10 bonus points for overall benefits which include environmental, social and economic benefits. Other national standards were referred to during the scoring exercise, e.g. Design Standard for Energy Efficiency in Public Buildings (GB 50189); Thermal Design Code for Civil Buildings (GB 50176); and Code for Indoor Environmental Pollution Control in Civil Buildings (GB 50325).

It is worth noting that green buildings in different countries are designed and built according to local climatic conditions and to suit the requirements of the locals. Therefore, the assessment criteria for these green building are different. This is reflected in the fact that the points allocated for water efficiency are different in LEED and GBCA rating tools. For example, landscape water efficiency accounts for 8.3% of total points available for water category in GBCA Green Star Office V3 tool whereas for as high as 40% in LEED New Construction and Major Renovation tool. There is even the case in different states of Australia when applying the same GBCA rating tool. For instance, Water category receives a weighting of as low as 10% in Northern Territory and Queensland; and as high as 15% in South Australia, Tasmania and Victoria in GBCA Green Star Healthcare V1 tool. This is arguably due to the more significant issue associated with water resources in these three states.

There are also extensive studies focusing on developing new green building rating tools (or customizing existing tools) to accommodate specific local context such as climatic conditions, economic development level and geographic conditions. For instance, Ali and Al Nsairat designed the SABA Green Building Rating System for Jordan by means of in-depth interviews with experts with a reference to leading green building rating tools such as LEED, BREEAM and GBTool [7]. Compare to these leading tools, the SABA Green Building Rating System places more focus on social sustainability and economic sustainability. In addition, water efficiency and energy efficiency accounts for more than 50% of the total number of points available in SABA Green Building Rating System due to water and resource issues in local area [7]. This percentage is comparatively higher than other green building assessment tools. Similarly, the heating related energy consumption received comparatively higher level of importance due to the general wet and cool climatic condition in the local area. Indeed, the green building assessment tools developed in different countries have taken the urban climate research findings into consideration to deal with various climate change issues such as urban heat island [8].

3.2. Technical and environmental aspects

Traditionally the focus of green building studies is placed on environmental aspect of sustainability. Taking the GBCA Green Star Healthcare V1 as example, 87% of unweighted points are related to environmental sustainability. It is also evidenced in the extensive studies on environmental sustainability of buildings, e.g. energy efficiency, water efficiency, resource efficiency and greenhouse gas emission reduction [9–14]. For instance, fly ashes could be used for structural components of green building design which helps to not only save the energy but also reduce the waste to the landfill [15,16]. Similarly, the utilization of precast or prefabrication technologies helps to reduce the amount of construction and demolition waste to a large extent [17]. Indeed, utilizing precast slabs in temporary construction works have a number of benefits such as mitigation of obsolescence and cost savings [18]. Rajagopalan and Leung's study found that the acoustic performance (measured by sound absorption and reverberation time) of precast panel which is made of concrete waste, is satisfactory in sports hall buildings [19]. In addition, prefabrication is recognized by both design and construction professionals as one of most common methods to prevent injuries particularly related to hazards of sustainable elements such as "construction at height, overhead, with energized electrical systems, and in confined spaces" [20]. Precast reinforced concrete panel and prefabricated steel are most common sustainable technologies in building 386 schools in Catalonia, Spain [21].

3.3. Social aspects

Last decades have witnessed growing concerns on social sustainability in buildings. This is due to the fact that the construction activities are a social process [22]. In the construction context, social sustainability mainly covers the quality of living, occupational health and safety, and future professional development opportunities [23,24]. Zhao et al. developed a framework to evaluate the corporate social responsibility performance of construction contractors by applying stakeholder theory at both the project level and company level [25]. The corporate social responsibility often featured in sustainability reported released by construction companies [26]. In building context, social sustainability means providing a healthy and safe environment to all stakeholders, e.g. construction personnel, users and operators which should be taken into account during sustainable design process [27]. Zuo et al. further argued that social sustainability in construction context should go beyond the individual building level towards the local community [24]. According to Valdes-Vasquez and Klotz, social sustainability should be taken into consideration in construction projects right from planning stage [28]. They suggested that social sustainability indicators include: engaging stakeholders including end users, assessment of social impacts, and consideration of local community. According to the Chartered Institute of Building, in some cases the corporate social responsibility performance even becomes one of key criteria when awarding contracts. This motivated the industry to place more focus on social sustainability of construction related activities.

Social sustainability was also reported as important aspects of green building and its assessment. Sarkis et al. proposed a novel framework for sustainability oriented contractor selection process by introducing social sustainability related indicators to the LEED framework [29]. This framework also provides a tool for formulating and developing teams. Lam et al.'s study found that stakeholder engagement, as part of social sustainability, is most critical to the implementation of green specification in construction, which is closely linked to green building assessment [30]. Ruano and Cruzado argued that sustainability education should be part of social dimension of green building assessment over the building's life cycle [31]. They recommended introducing a number of education related indicators to the existing green building rating tools. These indicators include: providing training in using public transport and bikes, awareness of local environmental issues,

knowledge on national and local sustainability related regulations, awareness of waste reduction and avoidance. Similarly, social and cultural benefits are identified as key outcomes of sustainable building envelope through improved energy performance [32]. Yuan and Zuo identified social sustainability aspects such as security within the campus and providing access to disability people as critical factors for green university alongside green building developments [33]. Mateus and Bragança suggested that social performance of green building assessment should cover: wellbeing and comfort of users, accessibility to public facilities, and level of awareness of sustainability issues [34].

3.4. Economic aspects

Berardi pointed out that there are social and economic requirements of green buildings such as access, education, inclusion, cohesion, affordability, economic value, impacts to local economy, indoor health, cultural perception and inspiration [35]. Popescu et al. pointed out that the benefits of energy retrofitting initiatives are reflected not only the cost savings derived from improved energy efficiency but also the potential value added to the property [36]. This helps to reduce the payback period of investment for energy efficiency measures.

Therefore, a green building could take either a narrow definition (e.g. purely environmental sustainability) or broad definition (i.e. adopting triple bottom line approach) [37,38]. However, the significance of social, economical and cultural aspects of sustainability of green building developments is rarely discussed [34]. Despite a large number of researches emphasizing the importance of these non-traditional dimensions of green building assessment, there is generally lack of in-depth empirical studies. Vast majority of green building related studies place focus on environmental aspect of sustainability (this will be discussed further in next subsection, how to achieve green buildings: technological approach).

3.5. Recent developments in green building assessment tools

The recent developments in green building rating tools reflect the change of direction of green building assessment towards recognition of social and economic aspects of sustainability. For instance, GBCA Green Star Communities rating tool is under pilot stage at the moment. It consists of six categories, i.e. Governance, Design, Liveability, Economic Prosperity, Environment and Innovation. This ground-breaking rating tool considers other aspects of sustainability than environment, e.g. social and economic. The environmental sustainability related credits only account for 26% of total points. The Governance category is similar to the Management category of other GBCA Green Star rating tools but expand the scope of management issues from project level to corporate level and community level. These include: corporate social responsibility, stakeholder management, and providing education opportunities for local community. For instance, 3 points will be awarded if Global Reporting Initiative (GRI) certified sustainability reporting is adopted at project and corporate level. Through Liveability category, 23% of points are awarded to the health and safety performance of green building developments. These include: provision of recreational facilities, supply of local food, adaptability of building, and integration with local transport network. Similarly, 19% of total points are awarded to economic viability of green building developments. The main indicators include: affordability, employment opportunities to the local community, and return of investment. There is similar structure and considerations in other neighborhood/community sustainability rating tools. The recognition of other dimensions of sustainability than environmental aspect in green building assessment tools showed an increasingly level of awareness and acceptance of triple bottom line approach.

4. Why green buildings and how much benefit?

There is no lack of studies investigating the costs and benefits associated with green building developments. The main purpose of these studies is to justify the value of going green which will assist decision making process. It is even more valuable under the context of Global Financial Crisis where clients have comparatively smaller finance capacity and financial institutions are more conservative in terms of lending decision. In essence, these studies focus on pros and cons of green building developments compared to conventional buildings. A common approach adopted in existing studies is to compare the characteristics of green buildings to those of conventional buildings such as energy efficiency, water efficiency, indoor environmental quality, thermal comfort, health and productivity.

4.1. Environmental

It is well recognized that there are a number of benefits associated with green buildings. From environmental perspective, green buildings help to improve the urban biodiversity and protect the eco-system by means of sustainable land use [39,40]. Reduction of construction and demolition waste is a critical component of sustainable building design [41,42]. Indeed, the recycling rate has to be above 90% in order to mitigate the obvious environmental impacts of construction and demolition waste which means reused and recycled materials in new buildings [43].

Compared with conventional buildings, green buildings generally provide higher performance reflected from energy efficiency, water efficiency and carbon emission reduction. Jo et al. stated that a large amount of CO_2 emission could be reduced (derived from energy efficiency) if LEED rating tools were adopted in all new construction works in Seoul [44]. Their study showed that commercial buildings will benefit most from LEED certification in terms of CO_2 reduction, followed by residential buildings and public buildings. Turner and Frankel found that the LEED certified building can achieve more than 28% of energy savings compared to the national average level (see Fig. 2) [45]. Among these buildings, library appears benefit most from LEED certification in terms of energy efficiency.

4.2. Economic

The cost savings are also associated with the improved building performance, particularly from the life cycle perspective. As a result, the operation cost is optimized. According to Economist,

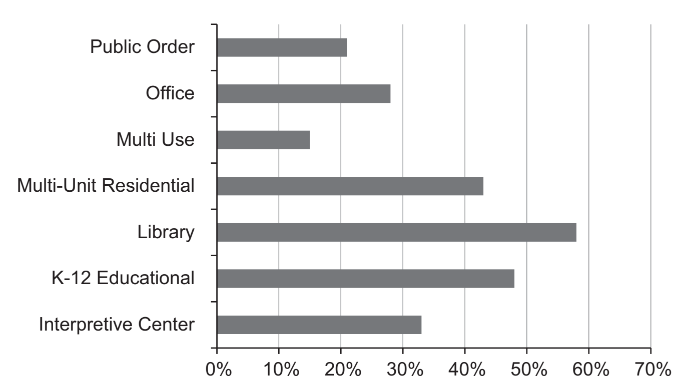


Fig. 2. Energy savings from LEED certified buildings, source: [45].

green building can save 30% of energy consumption than conventional buildings [46]. The research report released by Davis Langdon showed that extra upfront cost is required for green office building than conventional office buildings [47]. To achieve the GBCA Green 5 Star and 6 Star ratings, an extra construction cost of 4% and 10% are needed respectively. However, the cost of not going green is high as well, considering the carbon trade cost and rocket high energy price. The cost savings during the operation and maintenance stages will help to offset the upfront cost required for green building features.

Construction component (including labor and materials) accounts for the largest proportion of green building cost [48]. Ross et al.'s financial modeling also showed that LEED certified building will incur some 10% of extra cost (see Fig. 3). Their cash flow analysis showed that US$1.38/ft^2 savings per annum will be derived from green building design compared to conventional building. From maintenance perspective, green buildings perform better than conventional counterparts in terms of energy efficiency, water efficiency and cost efficiency, found by a study commissioned by the General Services Administration [49]. This is echoed by Lau et al.'s study which revealed that low energy office buildings with green features can save more than 55% of energy cost compared to conventional buildings [50].

4.3. Human aspects

Some scholars argued there are other benefits associated with green building that are not directly cost related. These studies placed focus on human aspects and benefits from green buildings. This is due to the fact that human beings stay in buildings for a considerable amount of time.

4.3.1. Thermal comfort

The satisfaction of building users is closely related to thermal comfort which is a complex dynamics of temperature and humidity [51–53]. This has attracted extensive attention from researchers to simulating and measuring the thermal comfort level in green building compared to conventional buildings. As a result, the range of room temperature required could be proposed [54,55]. Psychological, physiological, cultural and behavioral factors may play a role as well which attributes to adaptive thermal comfort [56–59].

4.3.2. Indoor environmental quality (IEQ)

One of most critical components of human benefits associated with green building is the indoor environmental quality (IEQ). The IEQ, including volatile organic compound emissions and other contaminants is another critical issue in buildings [60]. Therefore, IEQ features in all leading green building assessment tools [61]. Extensive studies have suggested that green building can achieve higher level of IEQ than conventional buildings, which helps to improve the health and productivity of occupants. As a result, the level of satisfaction of building users is enhanced. In fact, Leaman and Bordass's study found that users of green building tend to be more tolerant than those of conventional building in terms of indoor environmental quality [62].

Abbaszadeh et al. surveyed occupants of 180 buildings for their satisfaction of indoor environmental quality by utilizing 7 point Likert scale from −3 (very dissatisfied) to 3 (very satisfied) [63]. As shown in Fig. 4, green building generally outperformed conventional buildings except acoustics, lighting, and office layout. Their follow-up study found that most complaints to lighting are: not enough daylight, reflections in the computer screen, too dark or too bright. Top acoustic related complaints are: People talking in neighboring areas, People overhearing my private conversations, and People talking on the phone. It is worth noting that occupants in green buildings are satisfied with thermal comfort whereas those in conventional buildings showed more dissatisfaction.

Lee and Guerin adopted a similar methodology with Abbaszadeh et al.'s study to examine occupants' satisfaction and performance in green office buildings [64]. Their study found office furniture affects both satisfaction and performance of occupants in LEED certified office building significantly. Indoor air quality plays a critical role to building users' performance rather than their satisfaction. Other indoor environmental quality measures, e.g. office layout, acoustic, and thermal comfort are not statistically significant in terms of impacts on occupants in green buildings. This is supported by Zhang and Altan's study which found that users of green building are more satisfied with thermal comfort and visual comfort than those in conventional building however the acoustic satisfaction does not differentiate in these two buildings [51]. Frontczak et al.'s study also found a strong correlation between noise level, visual privacy and satisfaction with the workplace [65]. Opportunities to interact with co-workers and sufficient amount of light also contribute toward higher level of occupant satisfaction [65].

4.3.3. Health and productivity

Studies also found that the health conditions and level of productivity improve when occupants moved to green buildings [57,66,67]. For instance, Ries et al. suggested that economic benefits of green building in terms of productivity and absenteeism should not be overlooked [68]. Their study found an increase of 25% of productivity and the absenteeism is significantly reduced when occupants moved from a conventional building to a green building. Armitage et al.'s study with a survey of 31 GBCA certified office buildings showed that employers rather than employees recognized the health and productivity benefits associated with Green Office [69]. Hwang and Kim surveyed more than 200 office

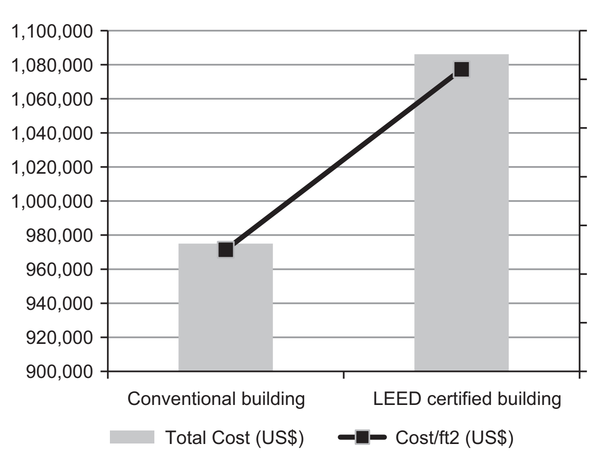


Fig. 3. Total cost and cost per unit of floor area, conventional building vs. LEED certified buildings, source: [48].

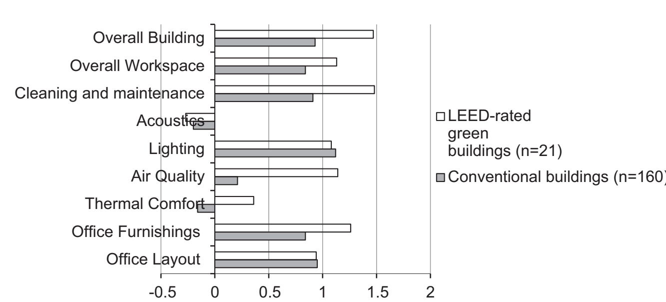


Fig. 4. Level of occupant satisfaction on indoor environmental quality, conventional buildings vs. green buildings, source: [63].

workers about their visual comfort level [70]. Their study found that the level of visual comfort is associated with the indoor lighting environment such as illuminance distribution which consequently affects the psychological wellbeing and productivity of occupants. These health-related benefits bring in broader scope of green building such as social and economic sustainability rather than traditionally environmentally focused [6,71]. However, industry practitioners may not be aware of or be uncertain of productivity and health benefits associated with green buildings that were documented in the literature, arguably due to lack of uniform measures of these impacts [72]. Deuble and de Dear further suggested that occupant health and productivity should be integrated into the post occupancy evaluation process [59]. This will help to bridge the gap between client's expectation and design solutions in future green building developments.

The energy conservation should not be on the cost of health, satisfaction and productivity of building users [73–75]. Indeed, it presents a complex issue to maintain a fine balance between indoor environmental quality and energy and cost-efficient operation of the heating, ventilating and air-conditioning (HVAC) plants [76].

4.3.4. *Criticisms*

There is no lack of negative experience with green buildings. The higher upfront cost presents one of most significant issues to the investors. Under the current macroeconomic environment, it is difficult to convince clients to inject extra investment on green features to their developments.

In addition, some studies have reported thermal comfort issues associated with green buildings such as high level of humidity, higher temperature during summer, etc. [67,77]. Paul and Taylor disagreed with the overwhelming benefits of green building in terms of thermal comfort [78]. Their study found that there is no significant difference between thermal comfort level of green buildings and that of conventional buildings (equipped with heating, ventilating, and air-conditioning systems). According to some occupants, it is a serious concern without the control of the thermal environment inside the building such as temperature, ventilation, and lighting [79]. This is often associated with reduced satisfaction of building users [80–82]. Indeed, the control of temperature, health, ventilation and heating is ranked by occupants as one of most important factors for the refurbishment of historic buildings [83]. Other issues include: the privacy due to the open space, noise, fire performance of eco-materials, structural safety issues due to installation of small scale solar PV or wind turbines [69,84–89]. The privacy and noise issues associated with green buildings are usually related to the office layout [90,91].

Some studies questioned the real performance of green building such as energy efficiency and water efficiency. For instance, Newsham et al. Analyzed energy data of 100 LEED certified buildings in US which confirmed that LEED certified building achieved an average of 18%–39% of energy savings per floor area compared to conventional counterparts [92]. However, their study also highlighted some 30% of LEED certified buildings consume more energy than conventionally designed buildings. Scofield examined the same set of buildings by Newsham et al.'s study with a consideration of off-site energy consumption, i.e. the generation and delivery of electricity to the building [93]. His findings showed that the source energy does not differentiate between LEED certified buildings and conventional buildings. Menassa et al. examined the energy performance of 11 U.S. Navy LEED-Certified Buildings [94]. Their analysis showed that majority of these buildings did not achieve the mandatory energy and water efficiency target. In fact, the energy consumption of majority of these buildings is higher than the national average level. Sabapathy et al.'s study found that LEED facilities achieved higher energy efficiency however does not necessarily translate into energy cost savings due to a number of factors such as the type of lease agreement and types of occupants [95]. Feige et al. examined 2500 residential buildings in Switzerland which found that sustainability feature of dwellings (e.g. water efficiency, health and comfort) helped to increase rental price [96]. However, there is negative correlation between energy efficiency of residential property and their rental premium which is arguably due to lease structures (e.g. bundling the energy cost with the rent).

Therefore, more studies are required to provide evidence for cost benefit analysis of green buildings in a comprehensive manner so that decision making process is better informed. A longitudinal study helps to collect related data in a certain period of time. This will then allow a direct evidence-based comparison between performance of green buildings and that of conventional buildings.

5. How to achieve green building?

The critical success factors to achieve green building can generally fall into three categories, i.e. technical, managerial and behavioral. It is worth noting that these factors are usually interactive therefore a comprehensive consideration of them is required. These approaches to achieve green buildings are discussed in detail in the following sections.

5.1. *Technological*

Utilization of renewable energy technological innovations has been pivotal for achieving green building objectives and accreditation [38]. This is due to the fact that depletion of conventional energy resources (coal) and its associated environmental issues. As a result, renewable energy development and utilization of renewable energy in other sectors have become the priority of many governments that are reflected in relevant public policies. Building sector is no exception. There is certain number of credits for implementing renewable energy in green building assessment tools. Regardless on-grid connection or not (on-site or off-site), the utilization of renewable energy in buildings helps to reduce the energy consumption and emissions. The lack of infrastructure connecting the electricity generated from building sites to the power grid presents one of most significant challenges. The common renewable energy resources used in buildings include: solar heat water, solar PV, small scale wind turbine, geothermal heat pump, etc. [89,97,98]. Indeed, the utilization of renewable energy plays a crucial role to achieve (Net) zero energy building [99,100]. The utilization of solar desiccant cooling system helps to save as much as 60% of energy related cost [101]. Therefore, the building integrated renewable energy has become a crucial component of green building design and development [102,103]. The recent studies saw the emerging role of hybrid system in developing green buildings. For instance, Dagdougui et al. developed a dynamic model to optimize hybrid renewable energy system [104]. This model was applied in a case study building which included biomass, wind and solar PV. Their study found the environmental benefits are significant despite the absence of the energy storage system. However, the cost, maintenance, and operation of renewable energy system still present significant challenges to implement these technological innovations in green buildings [104,105].

Construction and demolition (C&D) waste control also plays a critical role to achieve green building [5]. This is reflected in the green building rating tools. For instance, 2 points will be awarded if 75% of C&D waste is recycled and reused as specified in the LEED framework. Similarly, there are 5 credits related to recycle and

reuse of building materials or components in GBCA Green Star Office Design V2 rating tool. These credits are assigned 13 points, which accounts for more than 50% of total points under the Material category. Saghafi and Hosseini suggested taking the embodied energy and embodied emission into consideration as major criteria of evaluating the recyclability and reusability of building materials; and as part of green building assessments [106]. Aye and Hes compared the green building rating tools in US (LEED), UK (BREEAM) and Australia (GBCA Green Star). Their study found that the reuse of 80% of office building components (e.g. structure, wall, floor and roof) in Australia can reduce around 20 kg/m^2 of carbon emission every year of the building life cycle [107].

One of key elements of sustainable building design is to reduce the consumption of resources and to improve the resource utilization efficiency [108,109]. One of common approaches is to reduce, recycle and reuse or construction and demolition waste [42,110]. It is a common approach by government to encourage green building materials and technologies in order to minimize construction and demolition waste [17,111]. Using scenario analysis approach, Coelho and de Brito argued that the adoption of the re-used and recycled materials into new construction can help to reduce the environment impacts of building activities significantly [43].

5.2. Life cycle assessment (LCA)

The life cycle assessment (LCA) approach is one of most popular method to analyze the technical aspects of green buildings. In essence, LCA considers a building as a system, while quantifying the material flow and energy consumption flow across various stages of the life cycle. The advantage of LCA is to go beyond the traditional study of focusing on a single stage by extending the investigation to other stages as well, e.g. manufacturing and transportation of materials; energy consumption, water consumption and GHG emissions during the operation stage. Since 1990, LCA has achieved wide implementation in building assessments. This is reflected in a recent discussion paper from the GBCA which emphasize utilizing LCA to assess the environmental impacts of building materials in green building assessment.

Referring to ISO 14040 and ISO 14044, LCA consists of four phases, i.e. goal and scope definition, inventory analysis, impact assessment, and results interpretation. LCA has been utilized to analyze the water consumption, energy consumption, carbon emission and cost of buildings [112]. The LCA can be applied to either the entire building or individual components or materials to evaluate their impacts on environment hence improve building design [113,114]. Mahlia et al. conducted life cycle costing assessment on lighting retrofitting in a university in Malaysia as the lighting accounted for 42% of total electricity consumption of buildings [115]. Their study found that the lighting retrofitting helps to reduce energy consumption by 17–40% which means a return of investment in 1–2.5 years with a consideration of electricity tariff and inflation. Kneifel focused on life cycle energy assessment of commercial buildings by adopting three variations of building design for 12 prototype buildings in 16 cities of US according to ASHRAE 90.1 design standards [116]. Their extensive modeling exercises showed that even conventional energy efficiency measures help to reduce at least 20% of energy consumption and 16% of carbon emissions. This saving can then be translated into cost savings which could be even more significant due to the rocket high electricity price. Similarly, LCA has been used to provide inputs for green material/product labeling system and consequently helps to optimize the building design [117–120]. Collinge et al. (2013) argued that indoor environmental quality should be incorporated into the life cycle assessment by introducing three new categories of impacts to the LCA system, i.e. chemical-specific impacts, non-chemical health impacts, and productivity/performance impacts [121]. Using a LEED Gold certified university building as a case study, they found that the building users, even been LEED certified, could be subject to cancer toxicity risks due to “upstream processes of the building's operating energy supply” [121].

5.3. Managerial

According to Häkkinen and Belloni, related organizational and procedural issues are major barriers for green building developments rather than the lack of innovative technological innovations or rating tools [122]. There are multiple managerial aspects of green buildings, i.e. project level, company level and market level.

At project level, specific project management skill sets are required for managing green buildings. According to Robichaud and Anantatmula, these differences include: involvement of specialist consultant on green buildings, adopting green building assessment methods such as LEED, providing green building related continuous education and training opportunities to employees, and engagement of external stakeholders [6]. Hwang and Tan's study found that many green building projects in Singapore were still procured via traditional Design-Bid-Build approach rather than integrated delivery method [123]. Li et al. grouped factors related to project management of green buildings into five groups, i.e. human resource, technological innovation, support from designers and top management, and the coordination between design consultants and construction team [124]. Ofori-Boadu et al. interviewed top green contractors in US and concluded their project management practices on LEED projects [125]. These common project management practices include: investment on LEED; membership of the green building council; propaganda on green building developments; dedicated department for green buildings; collaboration with other contractors with LEED certification; and familiar with LEED system and related documentation.

At company level, the implementation of environmental management system (EMS) help to save 90% of energy consumption, reduce 63% of C&D waste, reduce 70% of water consumption, lower 20% of accident rate and 80% of quality complaints [126]. In addition, the cost predictability is enhanced which in turn eases the cost management pressure. The commitments from top management are essential for the planning of green building developments [127]. The green specification (e.g. database on green products and related technical standards) enhances the awareness of project team to gain access resources necessary for sustainable construction [128]. The sustainability reporting practices also gained growing attention from construction related businesses however vast majority of related studies placed focus on large scale international contractors [26]. Due to limited resources, most of small to medium sized firms have not adopted sustainability reporting practice [129,130].

Managerial issues also exist at the market level, mainly focusing on the health of the entire green building market. Love et al. conducted an in-depth analysis of a 6 Star Green Star office building in Perth in order to explore the slow take up of green building market in the local area [131]. Similar to other sustainability initiatives, green building is to a large extent dependent on public policies. The function of public policy can be either positive or negative incentives (i.e. penalties and compensations). As an initiative of the Council of Australian Governments (COAG), the Commercial Building Disclosure (CBD) Program mandates the disclosure of building performance information (e.g. energy efficiency and greenhouse gas emission) to buyers or tenants. This mandate applies to those commercial office buildings with more

than 2000 m^2 of space [132]. A Building Energy Efficiency Certificate (BEEC), containing information such as the National Australian Built Environment Rating System (NABERS) Energy star rating, has to be secured prior to sale, lease or sublease or the commercial property fulfilling the above criterion. This certificate is only valid for 12 months [132]. This serves as an incentive for developers and building owners to develop more high performance buildings or to retrofit existing buildings [133,134]. Indeed, the public policies play a significant role in the building energy efficiency and related sectors such as renewable energy developments [102,135,136].

5.4. Behavioral/cultural

The behavioral and cultural factors are also crucial for green building developments [59,137,138]. Therefore, it is critical to raise the level of awareness of all stakeholders (e.g. clients, designers, contractors, and end users) on concepts of sustainable development and green buildings. According to Hoffman and Henn, there are a large number of social and psychological related barriers to the implementation of green buildings such as over discounting the future, egocentrism, positive illusions and presumed associations [139]. Indeed, they stated that "… [for the adoption of green building practices and LEED certification], obstacles faced by the green building movement are no longer primarily technological and economic. Instead, they are social and psychological." (p.391) [139]. Based on a survey of occupants of GBCA certified office buildings, Kato et al. suggested that the benefits of green star certification are more psychological oriented (e.g. feeling good in such work environment) than physical (e.g. improved health and productivity) [140]. McCunn and Gifford's study, however suggested that there is no statistically significant relationship between sustainable features of office and the attitudes and behaviors of employees toward environment [141]. This is supported by Rashid et al.'s study which further pointed out that green building does not necessary improve the organization image directly [142]. Rather, organization image is improved by green building indirectly due to higher level of satisfaction of occupants [142]. Chau et al. applied discrete choice experiments to examine the attitudes of residents in Hong Kong toward green attributes of residential property [143]. Their study found that residents prefer to pay more on energy efficiency measures than other green building attributes such as water efficiency, indoor air quality and noise control. Such attitude and behavior of end users play a critical role in promoting green buildings. Therefore, some education or even government campaign could be an effective approach to raise residents' awareness of sustainability issues and willingness to pay for green building features.

6. Conclusions

This study reported a critical review of existing studies related to green buildings worldwide. The results showed that these studies can generally be classified into three categories, i.e. the definition and scope of green buildings; benefits and costs of green buildings; and ways to achieve green building. The extensive literature review shows that most of green building studies focus on environmental aspects of sustainability such as energy consumption, water efficiency and greenhouse gas emission together with the technical solutions. The studies on social and economic aspects of sustainability are comparatively lean, despite a large number of literatures emphasizing their importance. The social performance, for example, of green building warrants further investigation. The life cycle assessment approach, which has been extensively applied into the environmental and technical aspects of green building, will be a useful tool for social sustainability as well. However, it is a positive move from leading green building rating tools such as LEED, BREEAM and GBCA Green Star starting to introduce these features into the newly released version. More studies in these fields are required to support the new rating tool development and to assist the decision making process from client or end user's perspective.

The review also showed that there is a move from focusing on building itself only to the interaction between building and its users. Some studies have reported the impacts of thermal comfort and IEQ on occupants' satisfaction, performance and health conditions. Indeed, there have been claims that the occupants are largely overlooked in green building studies. The provision of education and trainings to occupants will help to regulate their behavior of using buildings which may affect the building performance significantly. The debate on cost and benefits of green building are noticeable. More robust studies are needed to enable evidence-based decision by the client and project team.

Similarly, the advanced information and communication technologies will play a crucial role to assist the development of green building. Building Information Modeling (BIM), for instance, can be applied to facilitate the green building certification process. There have been some studies reporting these practices [27,144,145] however the total volume of these papers is comparatively small. More studies are required to explore the best practice of integrating BIM into the various life cycle stages of the green building delivery.

More robust studies are required to validate real performance of green building via Post-occupancy Evaluation (POE). Similarly, vast majority of these studies focus on commercial buildings such as offices. As other major proportions of building stock, the residential buildings and industrial buildings deserve further studies in terms of their real performance. User survey such as BUS is an effective tool for such purpose.

It is worth noting that all leading green building assessment tools such as LEED, BREEAM and GBCA Green Star are designed according to local climatic and geographic conditions. The benchmarking study needs to take this into consideration when comparing the effectiveness of these green building rating tools. This warrants further investigation in future research.

Vast majority of existing studies on green building are based on the current weather data, e.g. Modeling the energy savings according to the historic climatic information. Similarly, the current occupancy pattern such as population and density were used to optimize building design and construction. This may not be sufficient as the future climatic conditions may change. Therefore, design and construction of green buildings need to consider future proofing. This is very useful considering the forecast that the extreme weather will be even more severe and longer duration [146].

Similarly, special population such as aged people, students and teachers could be paid more attention. Aged people are more vulnerable to overheating and indoor environmental quality. Students will become the practitioner in the future, even the leaders in various sectors. Teachers play a critical role to shape the attitude and behavior of students towards the sustainability related issues such as the manner of using buildings. The aforementioned issues serve as items of future agenda for green building related research.

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